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Basin evolution and destruction in an Early Proterozoic continental margin: the Rinkian fold–thrust belt of central West Greenland

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Abstract: In central West Greenland, early Palaeoproterozoic siliciclastic and carbonate sequences of the Karrat Group (shelf sequences of the Rae craton margin) were deposited in sedimentary basins controlled by NW- and SW-trending linked extensional fault systems. The shelf basins were later filled and overtopped by turbidite systems filling a foredeep advancing ahead of a thrust system – the Karrat Fjord thrust system – that propagated west to east. Deformation culminated in emplacement of basement-cored nappes, progressive deformation and high-grade metamorphism at c. 1.87 Ga. Reactivation of lower plate growth faults formed dome- and basin-like folds and related thrusts that refolded the structure of the Karrat Fjord thrust system and inverted the shelf basins. The southern Karrat Fjord thrust system was reworked in a belt of intense ductile NW-directed thrusting – the Nunaarsussuaq thrust system – formed at c. 1.84 Ga at the northern limit of the Nagssugtoqidian orogen. Kinematics of these events are at odds with the consensus view that the Rinkian fold–thrust belt is a northward extension of the Nagssugtoqidian orogen resulting from north–south convergence between the Rae and North Atlantic cratons. Application of structural restoration techniques to basin analysis of Palaeoproterozoic rocks has potential to provide new insights into Proterozoic orogenic processes worldwide.

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The Rinkian fold–thrust belt was recognized as a discrete Palaeoproterozoic geological entity by Escher & Pulvertaft (1976) based on structural style and the observation that it contained a distinctive stratigraphic sequence, the Karrat Group, thought to have been deposited on a continental margin. The Rinkian is located north of the Nagssugtoqidian orogen (Connelly *et al.* 2000; van Gool *et al.* 2002) and there have been several attempts to integrate its geology into the contemporary plate-tectonic framework of North America and Greenland (Hoffman 1990; van Kranendonk *et al.* 1993; Corrigan *et al.* 2009; St-Onge *et al.* 2009; Partin *et al.* 2014; Wodicka *et al.* 2014). Major uncertainties remain, partly owing to difficulty of structural and stratigraphic correlation across Baffin Bay into Baffin Island and partly owing to the relatively narrow strip of exposure along the Greenland coast so that no structures there can be traced a great distance. As a result, it is surprisingly difficult to establish the overall strike of the belt in West Greenland. Connelly *et al.* (2006) have shown that the Nagssugtoqidian orogen and the Rinkian belt may be linked through the northern part of Disko Bugt and that, if so, they define a single orogen, the Nagssugtoqidian–Rinkian orogen, that they thought to be >1100 km wide and to stretch from the Nagssugtoqidian foreland in the Søndre Strømfjord district far northwards into Melville Bugt (Fig. 1).

We present new data relevant to the basins in which the distinctive stratigraphy of the Karrat Group was deposited and to their subsequent polyphase structural evolution. We focus on the area of the Rinkian located between the great peninsulas of Nunavik (Svartenhuk Halvø) and Nuussuaq in Uummannaq commune (Fig. 1). This region was systematically mapped in the 1960s at a scale of 1:100 000 by the Geological Survey of Greenland (formerly GGU and now GEUS, the Geological Survey of Denmark and Greenland) but not described in memoir format until much later (Henderson & Pulvertaft 1987). The aim here is to elucidate the depositional setting and geometry of structural inversion of the Karrat Group basins in the Uummannaq region during the formation

of the Rinkian orogen. We build on the seminal work that flowed from systematic survey mapping (Henderson & Pulvertaft 1967; Henderson 1969; Pulvertaft 1973) and develop subsequent attempts to explain the structural history (Grocott *et al.* 1987; Grocott & Pulvertaft 1990) based on observations made during new fieldwork. The outcomes provide insight into previously obscure fundamental characteristics of the Rinkian fold–thrust belt, including strike of the orogen, pattern of metamorphic grade zonation and large-scale vergence, direction to the foreland and tectonic transport direction(s), and constrain future attempts to reconstruct the Palaeoproterozoic plate-tectonic framework of the Canadian and Greenland margins of Baffin Bay.

Karrat Group

The Karrat Group is widely exposed in the Uummannaq region and northward to the Melville Bugt (Fig. 1). It was given a formal definition during mapping by GGU comprising two units of formation status: the shallow shelf-type, largely clastic sedimentary rocks of the Qeqertarsuaq Formation and the greywacke–flysch of the overlying Nûkavsak Formation (Fig. 2) (Henderson & Pulvertaft 1967; Escher & Stecher 1978, 1980). At the time of the original research it was established that these rocks represented a sedimentary cover originally deposited on a basement of Archaean high-grade gneisses and subsequently deformed and metamorphosed; processes that it was thought had erased the angular unconformity between basement and cover. Only when later investigations (Garde & Pulvertaft 1976) revealed that an angular unconformity had in fact been preserved at the base of an extensive unit of shelf-type carbonate rocks called the Marmorilik Formation (Fig. 2), previously erroneously assigned to Archaean basement, did it become possible to correlate the Qeqertarsuaq and Marmorilik formations and assume a Palaeoproterozoic age for the Karrat Group as a whole (Garde 1978; Henderson & Pulvertaft 1987).

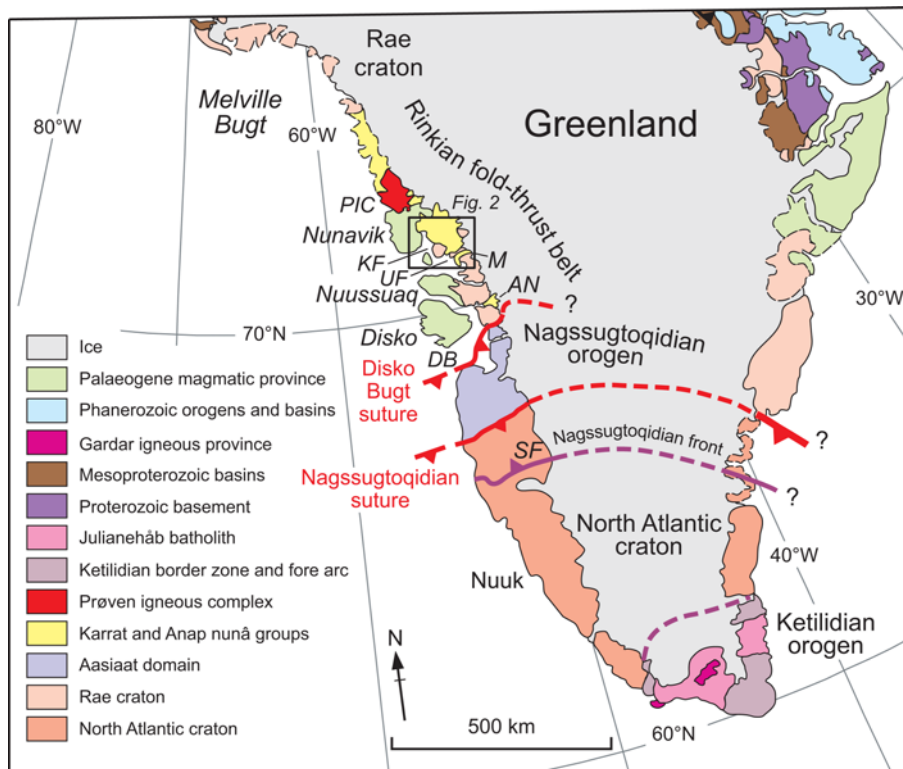


Fig. 1. The main geological provinces and boundaries of Greenland. The Rinkian fold-thrust belt is a broad belt of deformation in the Rae craton that formed the lower plate of the Nagssugtoqidian suture. Tectonic subdivisions and boundaries within the Rinkian fold-thrust belt are uncertain although many of the major elements of the geology including the Palaeoproterozoic sedimentary cover sequences and the Prøven igneous complex (part of the Cumberland batholith) are present also on Baffin Island. PIC, Prøven Igneous Complex; KF, Karrat Fjord; UF, Uummannaq Fjord; M, Maarmorilik; AN, Anap Nuna; DB, Disko Bugt; SF, Søndre Strømfjord. Modified from St-Onge *et al.* (2009). Printed with permission from Geological Society, London.

Published age-data on the Karrat Group and its basement rocks are sparse but an age for Archaean orthogneiss from the Uummannaq district predates 3.0 Ga (Thrane *et al.* 2003) and zircon age spectra from the Karrat Group imply that the basement mainly comprises a suite of orthogneiss protoliths with an age range of 3.1–2.8 Ga metamorphosed at 2.8–2.7 Ga and reworked in the Palaeoproterozoic at 1.85–1.75 Ga (Connelly & Thrane 2005; Connelly *et al.* 2006). These studies show that as well as containing Archaean clastic material, the Nûkavsak Formation also contains Proterozoic detrital zircons with a clear peak of ages at *c.* 2.0 Ga and the youngest zircons having an age of *c.* 1.9 Ga (Thrane *et al.* 2003). The Nûkavsak Formation was intruded by the syntectonic, I-type Prøven igneous complex (Fig. 1) and related pegmatites at 1869 ± 9 Ma (Thrane *et al.* 2005), implying that deformation and high-grade metamorphism may have followed rapidly the deposition of the youngest rocks in the formation. The zircon data show that the bulk of the clastic material making up the Nûkavsak Formation was derived from a Palaeoproterozoic magmatic source, supporting the earlier conclusions of Kalsbeek *et al.* (1998) that the Nûkavsak Formation was deposited in a basin within an active margin setting. In contrast, most detrital zircons in the Qeqertarsuaq Formation are older than 2.5 Ga and the youngest zircon is older than 2.1 Ga (Thrane *et al.* 2003), consistent with a rift (passive margin) setting for the lower Karrat Group.

Qeqertarsuaq Formation

Stratigraphic columns for the Qeqertarsuaq Formation were constructed using data from geological survey maps supplemented by field observations and thicknesses calculated from cross-sections (Fig. 3). They were drawn for locations where there is thought to have been little duplication by thrusting or other significant structural thickening. We have used thickness and lithology variation expressed in the stratigraphic columns with a reinterpretation of outcrop patterns and a structural contour map drawn for the base of the Nûkavsak Formation (Henderson 1969) to infer the position of some of the main basin boundary faults that controlled the deposition of the formation (Fig. 3).

The Qeqertarsuaq Formation is thickest in the Inngia–Kangilleq dome and reaches 2400 m on the Ummammakku Nunaa peninsula where the principal lithologies are semi-pelitic to pelitic schist, quartzite and quartzite schist and rare marble (Figs 2 and 3). It is much thinner to the SE and elsewhere in the Uummannaq region, to the extent that it is only intermittently shown at 1:100 000 scale on the geological maps (Henderson & Pulvertaft 1967, 1987). All the rocks in the Qeqertarsuaq Formation are metamorphosed at upper amphibolite or middle amphibolite facies and contain a strong planar fabric that is transposed bedding. Depending on composition, porphyroblasts include staurolite and garnet and occasionally cordierite and albite. At the base of the formation, the planar fabric lies parallel to strong planar fabrics in the basement orthogneiss. No primary structures have been observed in the rocks of the Qeqertarsuaq Formation. Lithology and mineralogy are described in the geological survey memoir that accompanies map sheets Marmorilik (71V.2 Syd), Nûgâtsiaq (71V.2 Nord) and Pangnertôq (72V.2 Syd) (Henderson & Pulvertaft 1987).

Kangilleq Formation

A hornblende schist and amphibolite unit is a distinctive horizon at the top of the Qeqertarsuaq Formation (Figs 2 and 3). The rocks are typically intensely foliated but volcanic textures in recognizable pillow lavas and hyaloclastite tuffs are preserved on Nunavik (Grocott & Vissers 1984) and near Nuugaatsiaq on Qeqertarsuaq (Fig. 2). In the geological survey mapping, Henderson & Pulvertaft (1967, 1987) included this unit in the Qeqertarsuaq Formation. We prefer to adopt formation status for this horizon and name it the Kangilleq Formation because it is distinctive, has a regional distribution and is important for understanding the relative timing of structural events.

A lithologically similar, 80–100 m thick, compact amphibolite interleaved with Archaean gneisses crops out on Alfred Wegener Halvø (Fig. 2) and was given formation status, the Sermikavsak Formation, by survey geologists but assigned an Archaean age (Henderson & Pulvertaft 1967, 1987). Crucially, the Sermikavsak Formation on Alfred Wegener Halvø can be followed eastward from

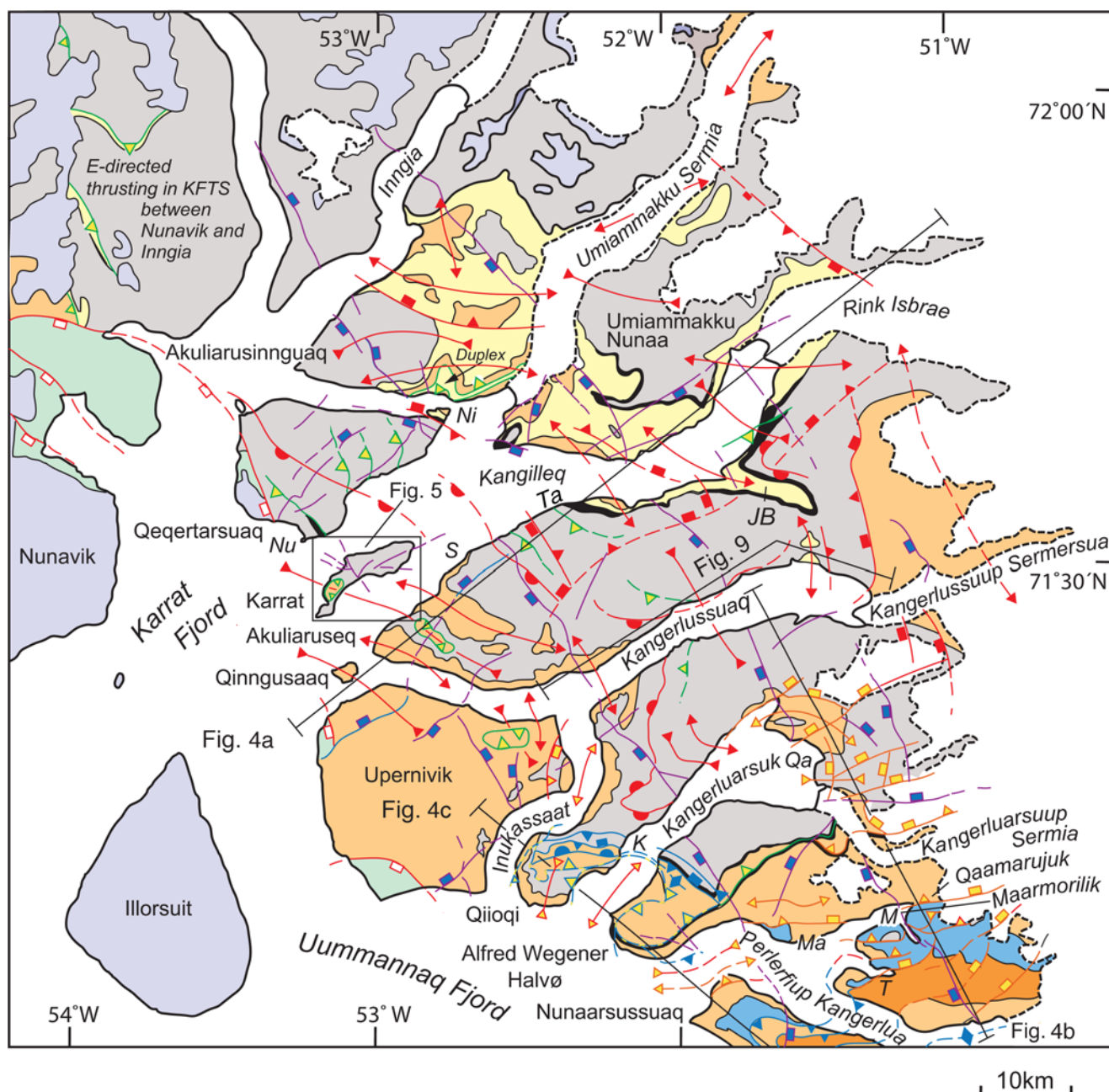


Fig. 2. Geological map of the Maarmorilik–Pangnertôq district of Uummannaq fjord region showing main stratigraphic boundaries and structures. Based on mapping by [Henderson & Pulvertaft \(1967, 1987\)](#) and a structure contour map for the base Nûkavsak Formation ([Henderson 1969](#)). New mapping by the authors in 2002–03 and 2012–13 resulting in the recognition of additional faults and a reinterpretation of some stratigraphic boundaries on the survey maps as faults. Ni, Niaqomakassak; Nu, Nuugaatsiaq; S, Saattukujooq; T, Tinumanikassaa; JB, Johannes Brae; Qa, Qaarsukassak; K, Kigarsima; Ma, Mallak; M, Maarmorilik; Ta, Tasiussaq.

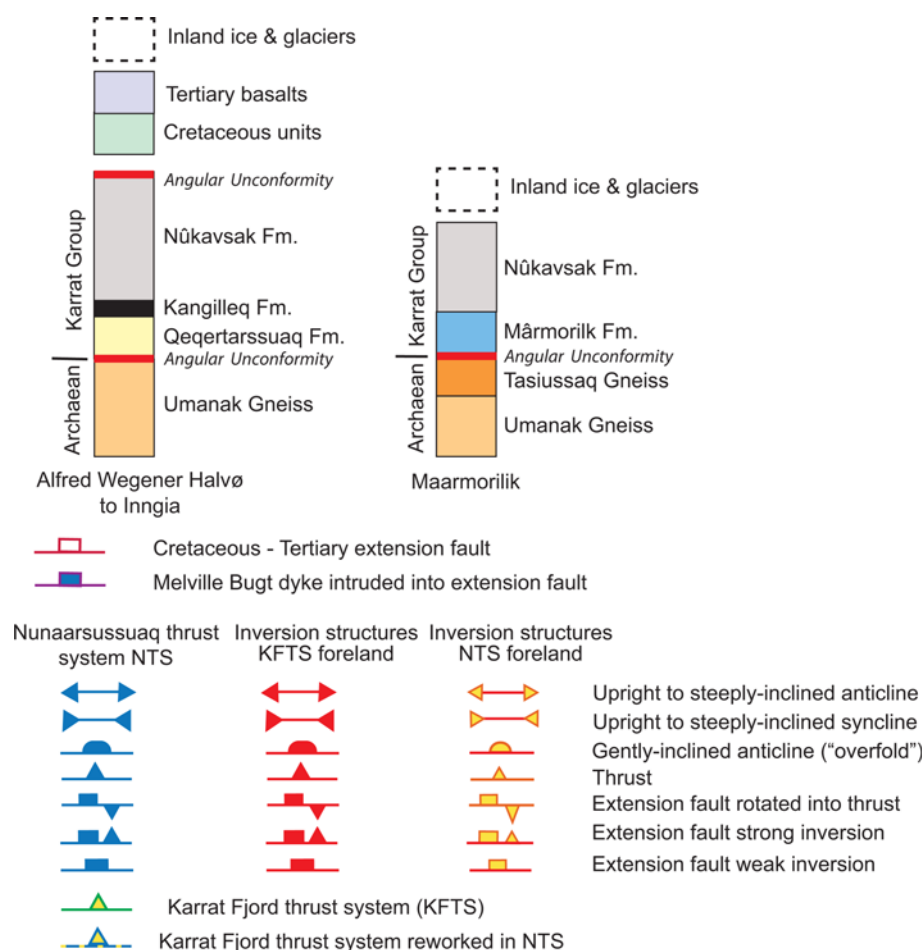
the western end of the peninsula to cliffs on each side of Kangerluarsuup Sermia (Fig. 2). Here, thrust sheets of basement gneiss, hornblende schist/amphibolite and biotite schists of the Nûkavsak Formation restore to a simple stratigraphic succession with Sermikavsak Formation at the base of the Nûkavsak Formation: the stratigraphic position of the Kangilleq Formation (Fig. 2). We have therefore reassigned the Sermikavsak Formation to the Karrat Group as the Kangilleq Formation and the original name is abandoned.

Mârmorilik Formation

The Mârmorilik Formation crops out in the Uummannaq Fjord district and is dominated by carbonate rocks (Figs 2 and 3). It plays host to the important but now exhausted Black Angel Pb–Zn

Mississippi Valley type (MVT) mineral deposit ([Pedersen 1980](#)). Near Maarmorilik, the formation lies with angular unconformity on a suite of weakly deformed Archaean I-type granitic plutonic complexes, the Umanak gneiss of [Henderson & Pulvertaft \(1967\)](#), which are probably similar in nature to the protolith of gneissic basement to the Karrat Group elsewhere.

The formation has a thickness of *c.* 1600 m with dolomite marbles dominant in the lower part and calcite marbles dominant above (Fig. 3) ([Garde 1978](#)). Faults that cut the Mârmorilik Formation are stitched by NNW-trending olivine dolerite dykes (Fig. 2). The dykes belong to the Melville Bugt dyke swarm ([Nielsen 1990](#)) and have a late Palaeoproterozoic age of *c.* 1645 Ma ([Kalsbeek & Taylor 1986](#)). A 1:20 000-scale geological map of the Mârmorilik Formation ([Garde 1978](#)) shows that the faults have a normal-slip offset in the basement–cover contact but much reduced

Fig. 2. *Continued.*

offset at higher levels within the formation itself. This is consistent with thicker time-equivalent sequences in the fault hanging wall than in the footwall and hence with synsedimentary faulting. A thin quartzite member at the base of the formation contains primary structures indicative of a shallow-water shelf environment. Recrystallization at greenschist-facies grade has obscured primary structures in overlying carbonate units although scapolite is common in dolomite marbles, implying that the sequence contained evaporates and was deposited in a sabkha environment (Garde 1978).

The formation is overlain by semi-pelitic rocks and metamorphosed greywacke sandstones of the Nûkavsak Formation (Pedersen & Gannicott 1980; Henderson & Pulvertaft 1987). This led Garde (1978) and Henderson & Pulvertaft (1987) to infer that the Qeqertarsuaq and Mârmorilik formations were time equivalent and their different geographical distribution implied that they accumulated in separate basins with different clastic input. The boundary was placed loosely along the axis of Alfred Wegener Halvø (Fig. 2) although not tied to any specific structure.

The Nûkavsak Formation

The Nûkavsak Formation comprises greywacke, sandstone and shale with a structural thickness of at least 5000 m attained on the north side of Kangerluarsuk (Henderson & Pulvertaft 1967) (Fig. 2). It is extensive and underlies much of three, half-degree survey map sheets; Mârmorilik (71V.2 Syd), Nûgâtsiaq (71V.2 Nord) and Pangnertôq (72V.2 Syd), overlying rocks of the Kangilleq and Qeqertarsuaq formations (Fig. 2). The Nûkavsak Formation is highly deformed by thrusts and chevron-style folds. It is metamorphosed in the upper greenschist facies reaching amphibolite facies at the base near the contact with the Kangilleq and Qeqertarsuaq formations. Thrust interleaving of basement and

cover is evident in the west but for the most part the Karra Group forms a simple cover to basement rocks and the Nûkavsak Formation is easy to recognize and define (Fig. 2). To the south, between Maarmorilik and Nuussuaq (Fig. 1), brown-weathered clastic metasedimentary rocks are also common interleaved with basement gneisses by thrusting and intense ductile deformation (Grocott 1984; Pulvertaft 1986; Grocott & Pulvertaft 1990). The metasedimentary rocks interleaved with gneisses include sparse but widely distributed marble units correlated with the Mârmorilik Formation (Pulvertaft 1986). For this reason, the brown-weathered semi-pelites and pelites may also be of Palaeoproterozoic age and correlatives of the Nûkavsak Formation.

The Nûkavsak Formation is exposed in areas of high Alpine relief in the northern part of the area but is accessible on eastern Nunavik and near the village of Nuugaatsiaq (Fig. 2). Despite folding and cleavage development, sedimentary structures include grading, parallel and small-scale cross-lamination, convolute lamination and climbing ripples (Grocott & Vissers 1984). Flute casts are very occasionally preserved and have been obscured nearly everywhere by flexural slip on bedding during intense folding. Parts of Bouma sequences and occasionally complete Bouma sequences can be found with channelling on a metre scale in some thicker sandstone beds, some of which amalgamate. Generally the beds consist of T_{c-e} intervals in thinning-upward bundles. No examples of large-scale channelling have been found. On Nunavik, Grocott & Vissers (1984) described a mega-breccia of limestone blocks in a sandstone matrix at the base of a submarine slide (olistostrome), which carried shelf-type lithologies into an outer- or mid-fan setting. In addition, there are kilometre-scale domains where the direction of structural facing (Shackleton 1957; Bell 1981) is down on the first cleavage and pre-cleavage minor folds are transected by the cleavage. This implies that kilometre-scale inverted limbs of large folds formed

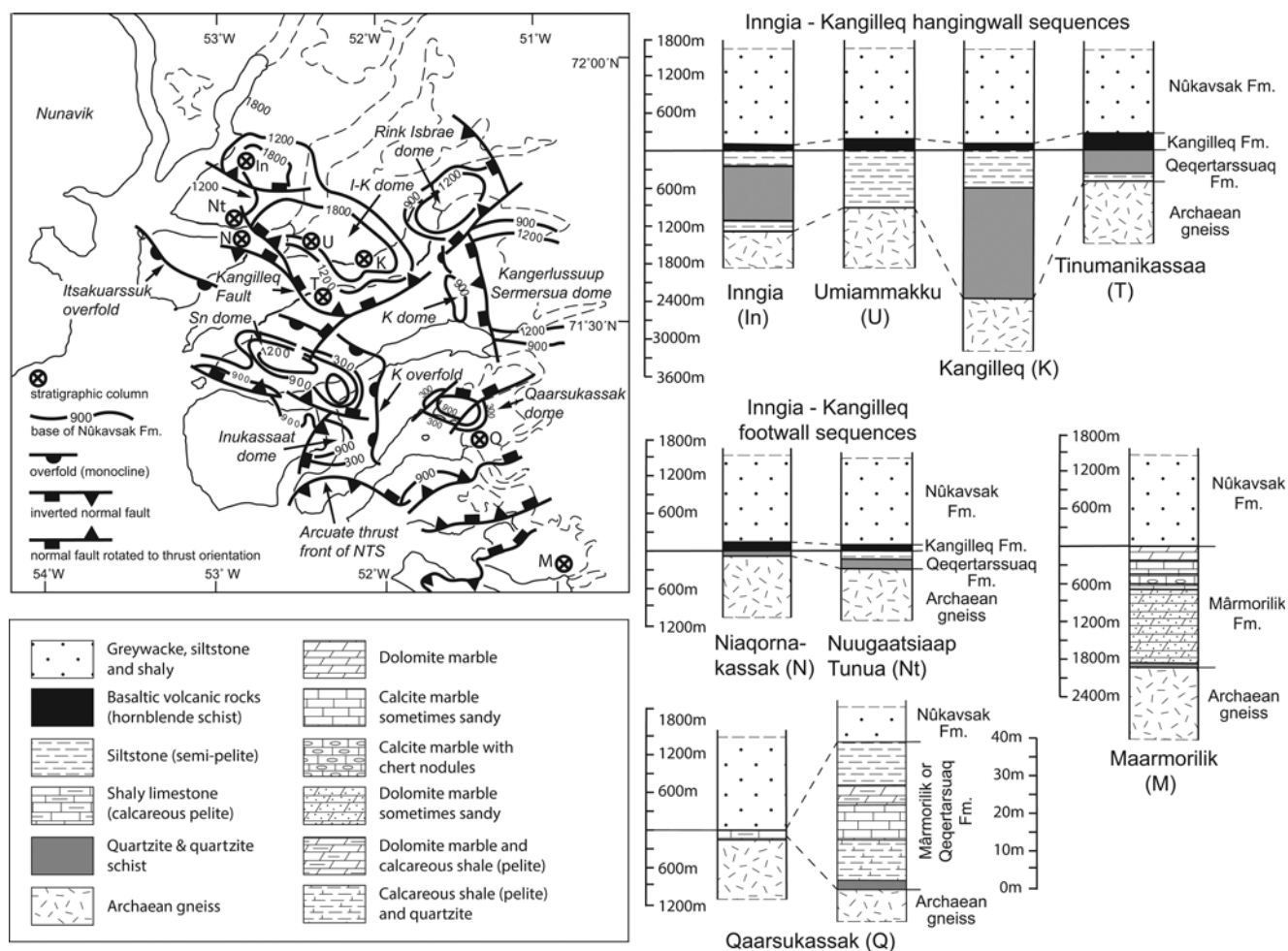


Fig. 3. Stratigraphic columns for the Qeqertarsuaq Formation drawn from the geological survey map supplemented by new field observations at Niaqornakassak (the type section for the Qeqertarsuaq Formation) and elsewhere. Thicknesses are calculated from cross-sections. The columns are chosen in areas where there is thought to have been little duplication by thrusting or other significant structural thickening. Structural contours are in metres to the base of Nûkavsak Formation, from Henderson (1969). I-K dome, Inngia–Kangilleq dome; Sn dome, Sneppyræmiden dome; K overfold, Kangerluarsuk overfold; In, Inngia; U, Umiammakku; K, Kangilleq; T, Tinumanikassaa; N, Niaqornakassak; Nu, Nuugaatsiaap Tunua; Q, Qaarsukassak; M, Maarmorilik.

before the rocks reached recrystallization temperatures and were able to sustain a cleavage.

The lower Nûkavsak Formation has been mapped in detail at the head of Kangerluarsuk (Fig. 2) (Marker & van Gool 2014). Fine- to medium-grained greywacke sandstones and mudstones cut by normal- and oblique-slip faults are stitched by late Palaeoproterozoic dykes of the Melville Bugt dyke swarm. At Qaarsukassak (Fig. 2), the lower Nûkavsak Formation is c. 1500 m thick and integrated mapping and resistivity geophysics used to determine depth to basement has revealed thickness variations in the hanging wall of extensional faults interpreted as synsedimentary growth-triangles (Marker & van Gool 2014). These faults were originally growth-faults and the lower part of the Nûkavsak Formation, like the Qeqertarsuaq Formation, is synrift. Overlying the synrift turbidites is a c. 1000 m sequence of graphitic pelites, evidence of an anoxic event in a starved basin, present also low in the Nûkavsak Formation on Nunavik and elsewhere (Grocott & Vissers 1984). These are interpreted as post-rift sediments deposited at the top of the Rae passive margin sequence. This begs the question: what was the tectonic setting for deposition of the overlying c. 5000 m of turbidite-facies rocks?

Karrat Fjord district: Karrat Fjord thrust system and its reactivated foreland

We have used regional cross-sections drawn in the transport direction and validated by restoration to analyse the geology of the

Rinkian fold–thrust belt. This technique imposes geometrical discipline on cross-section construction and is a powerful approach in structural analysis. It allows complete or partial restoration of the deformed cross-section as a geometrical test of validity and facilitates visualization of the geological history.

Three regional cross-sections were constructed to illustrate the structural evolution and in particular basin development and inversion (Fig. 4). Conventional validation techniques based on preservation of area between deformed and restored sections were used to ‘balance’ the sections and predict the trajectory of the underlying detachment faults to depth (Gibbs 1984, 1990). All cross-sections were validated by a three-step procedure. First, shortening on the late dome- and basin-like folds and related thrusts was restored maintaining the area of each fault block. The second step used Kangilleq Formation volcanic rocks, which include hyaloclastite tuffs deposited at or about sea level, to define a ‘regional’ line to which the top of horst- and footwall-blocks in half-grabens were restored. Finally, the shape of the major extensional faults in two dimensions was constructed using the ‘Chevron construction’ (Hossack 1979; Gibbs 1990). This method takes the position and dip of a fault at outcrop and uses the shape of a horizon in the fault hanging wall, in this case the restored Kangilleq Formation, to construct the fault shape to depth. This ensures that the modelled shape of the restored Kangilleq Formation and the position and shape of major faults are consistent. Sections were drawn perpendicular to the axial surface trace of major upright

folds: WSW–ENE for Figure 4a, NNW–SSE for Figure 4b and NW–SE for Figure 4c. The main uncertainty is the assumption that the transport direction for extensional faulting and inversion was in the plane of each section.

The Karrat Fjord thrust system: Karrat nappe and thrust sheet

A thick sequence of the Nûkavsak Formation has been intensely folded and shortened by thrusting in the Karrat Fjord thrust system

(green-coloured structures in Figs 2 and 4a). At Akuliaruseq (Fig. 2) a stack of two basement gneiss thrust sheets has been refolded by a 10 km-scale anticline, the Sneypyramiden dome (Figs 3 and 4a). The upper thrust sheet is exposed also on Karrat and farther south in a klippe on Upernivik (Fig. 2). On Karrat, basement gneiss lies above an apparently upside-down section comprising Qeqertarsuaq, Kangilleq and Nûkavsak formations (Fig. 5). There are no way-up criteria in these highly deformed rocks but if they are indeed inverted, as opposed to having had their stratigraphic sequence neatly reversed by thrust imbrication, this implies that a

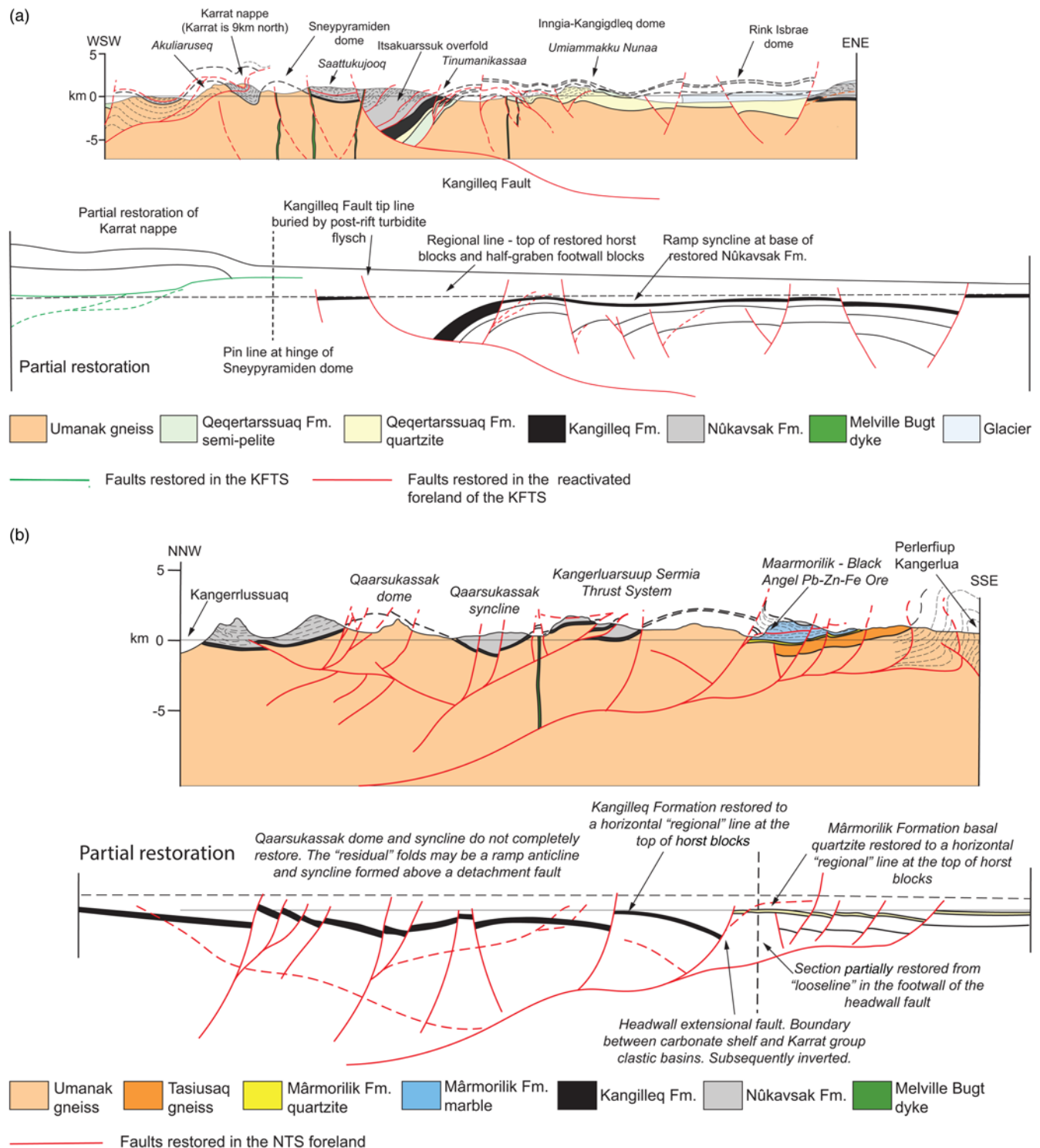


Fig. 4. Cross-sections through the Uummannaq region. (a) Karrat Fjord district: western Upernivik Ø to Rink Isbrae. (b) Uummannaq Fjord district: Kangerlussuaq to Maarmorilik. (c) Uummannaq Fjord district: Inukassaat to Nunaarsussuaq. Vertical and horizontal scales are equal. Faults in (a) and (c) colour-coded on the partial restoration as in Figure 2.

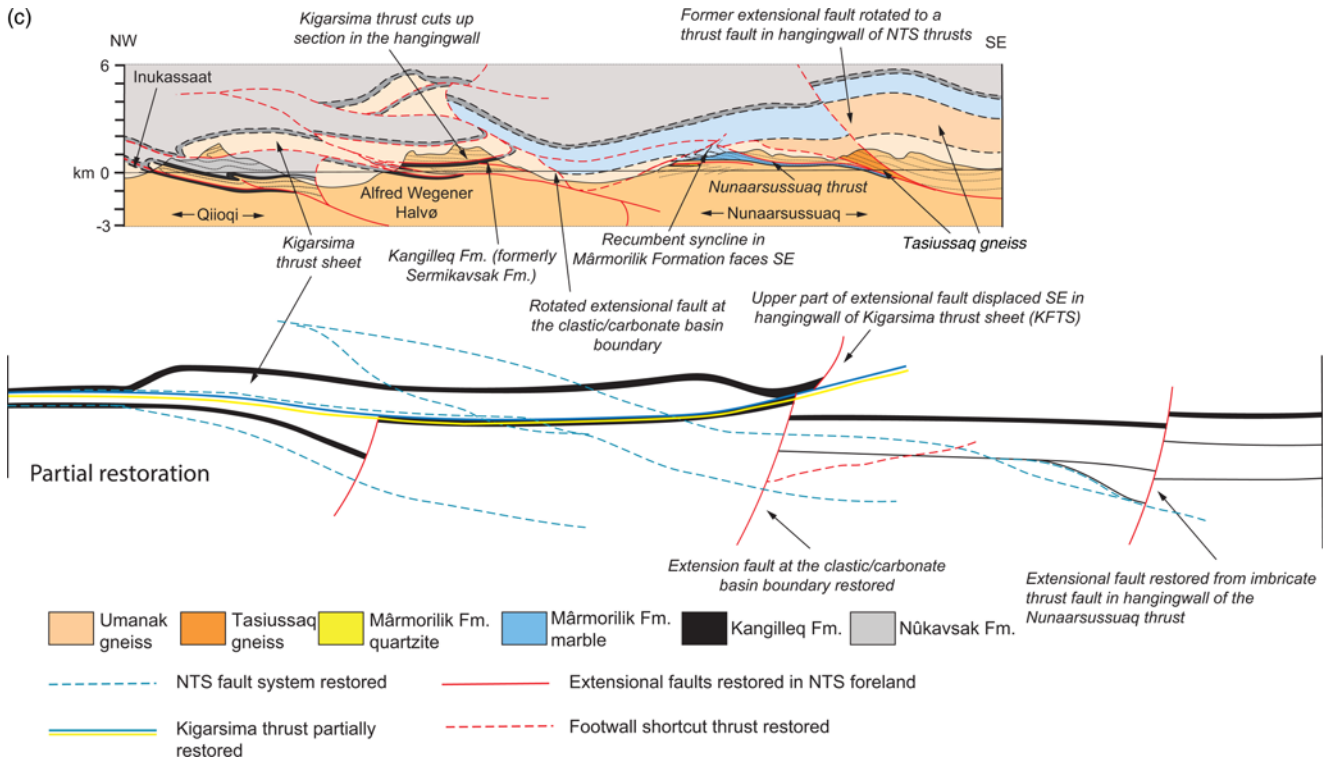


Fig. 4. Continued.

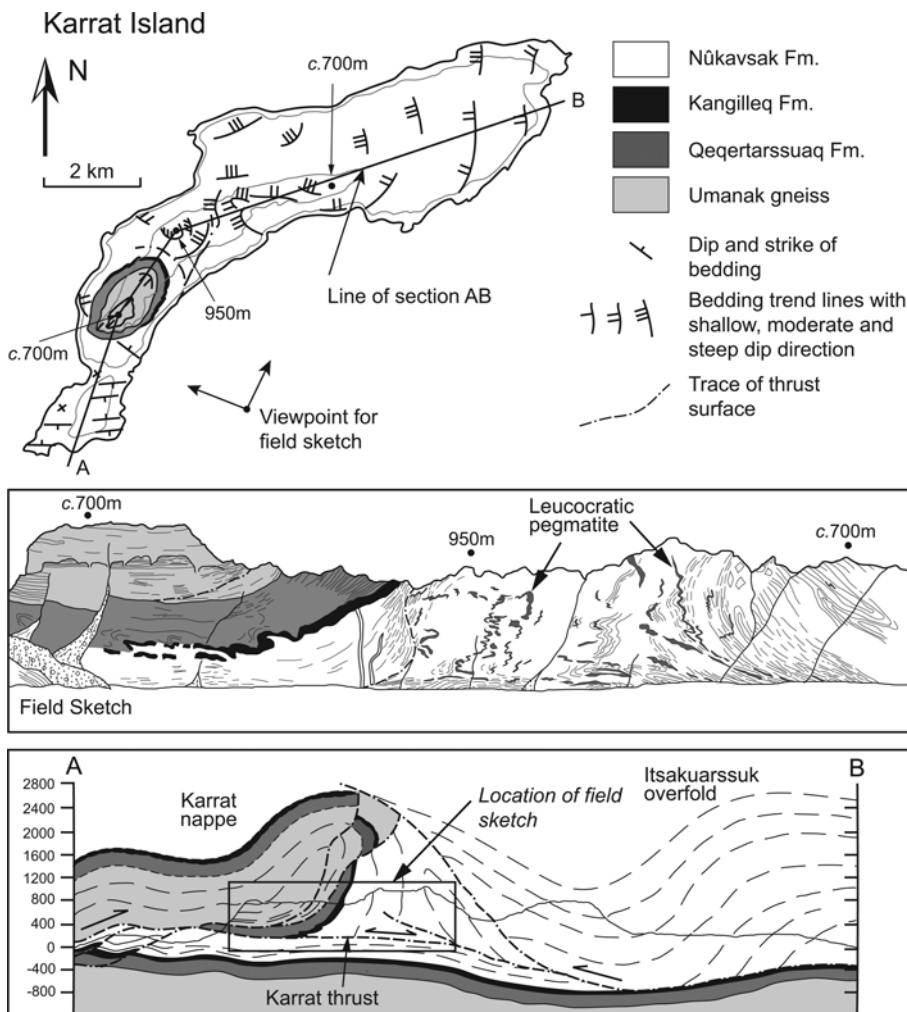


Fig. 5. Structure of Karrat: the Kigarsima nappe and Itsakuarsuk overfold. Bedding trend lines on the map are from Henderson & Pulvertaft (1987). The leucocratic pegmatites in Nükavsak Formation between spot heights 950 and 700 m on the field sketch were intruded late- to post-cleavage in the Karrat Fjord thrust system, after emplacement of the Karrat thrust and before development of the Itsakuarsuk overfold. The axial surfaces of minor folds in the pegmatite are parallel to a crenulation cleavage in the host Nükavsak Formation, which is axial planar to the Itsakuarsuk overfold.

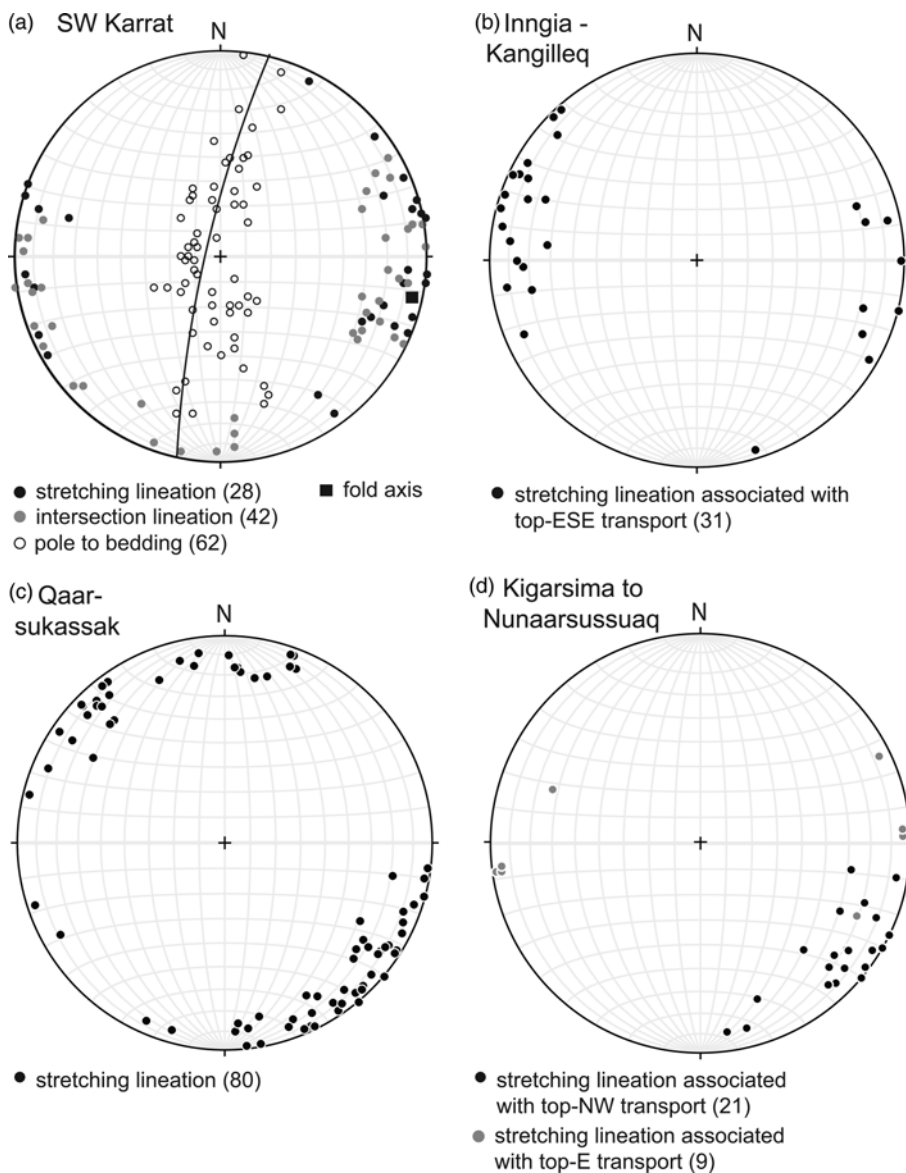


Fig. 6. Mineral and shape fabric lineations. (a) Mineral lineations, shape fabric lineations and intersection lineations, Karrat. (b) Mineral and shape fabric lineations, Inngia-Kangilleq dome. (c) Mineral lineations, Qaarsukassak. (d) Mineral and shape fabric lineations, outer parts of Qioqi (Kigarsima), Alfred Wegener Halvø and on Nunaarsussuaq. Equal area Lambert projections.

fold nappe has been eroded from above the present-day exposures on the island. This is our preferred interpretation (Fig. 5). The thrust underlying the nappe, the Karrat thrust, is located in a gently east-dipping, high-grade ductile shear zone exposed at sea level. In west Karrat, this shear zone is a c. 250 m thick high-grade shear zone of mylonitic metasandstones (diopside grade) and pelites (migmatite grade). In pelites and at the bedding contacts between pelites and metasandstones, where deformation is high but the fabric not mylonitic, intersection lineations between cleavage and bedding plunge gently SSW (Fig. 6a). With increase in intensity of the planar fabric, and development of porphyroblast fabrics, the intersection lineation rotates to east-west or ENE-WSW, parallel to a stretching lineation defined by hornblende and biotite mineral lineations and a quartz shape fabric. Thrusts cut up through the planar fabric to the ENE viewed parallel to the stretching lineation (Fig. 5). This implies that the Karrat thrust was emplaced by transport to the ENE.

Itsakuarssuk overfold: a basin inversion monocline

A large-scale monocline, the Itsakuarssuk 'overfold' (Henderson 1969), is present in the Nūkavsak Formation of eastern Karrat and western Qeqertarsuaq (Figs 2, 3, 4a and 5). It can be traced NW into Nunavik and has an along-strike length of at least c. 50 km (Fig. 3). The overfold formed relatively late in the structural history. In

Nunavik, Qeqertarsuaq and Karrat, gently to moderately inclined minor folds, crenulations and crenulation cleavage axial planar to the overfold are superimposed on east-vergent folds and cleavage of the Karrat Fjord thrust system. The overfold is west-vergent and on Karrat it overlies the same major ductile shear zone that, to the west, contains the Karrat thrust (Fig. 5). Below the overfold, biotite mineral lineations and quartz shape fabric lineations trend east-west in the shear zone. Viewed parallel to the lineation, the rotation sense of planar fabrics into the high-strain zone (bedding in the limb of the overfold, the axial planes of minor folds and crenulation cleavage) shows that transport was to the west. Therefore, there have been two displacements on the shear zone; first to the east or ENE during emplacement of the Karrat thrust sheet and then to the west during formation of the overfold. The cliffs of the island show that the Karrat nappe and thrust system and the overfold form a large-scale triangle zone above this shear zone (Fig. 5).

The Itsakuarssuk overfold can be traced to the south shore of Kangilleq between Saattukujooq and Tinumanikassaa (Figs 2 and 4a). Here, there is an abrupt increase in thickness of the Kangilleq and Qeqertarsuaq formations in the steep limb of the monocline (Fig. 4a). The thickness change is interpreted to take place across a synsedimentary growth fault. This fault, the Kangilleq Fault (Fig. 3), is not obvious at outcrop and, without reactivation, it would probably have remained blind owing to truncation by thrusts

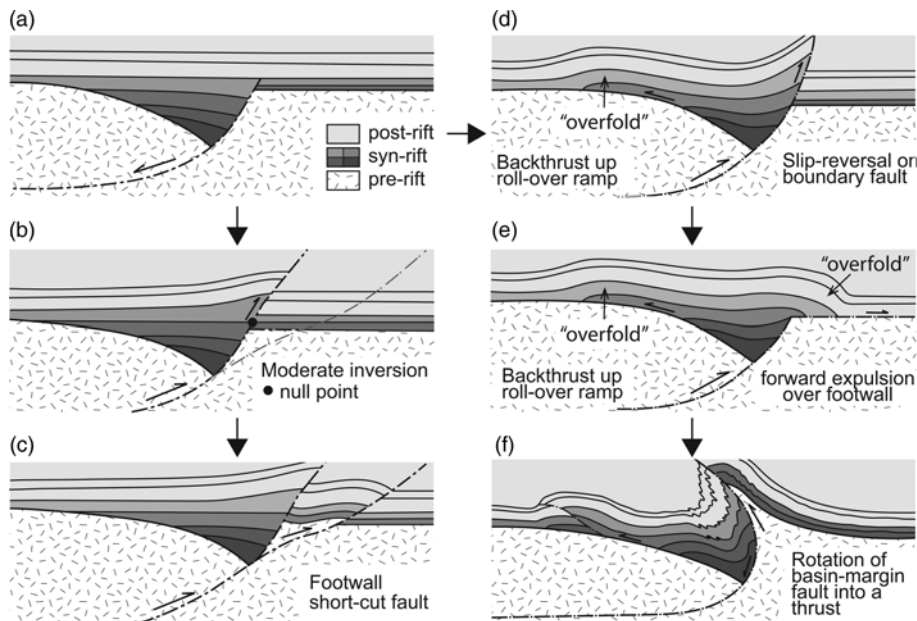


Fig. 7. Models of inversion tectonics. (a) Half-graben controlled by a listric normal-slip fault showing a roll-over anticline in the fault hanging wall. Pre-, syn- and post-rift sediments in the accommodation space created by slip on the fault. (b) Moderate inversion owing to fault reactivation in contraction (positive inversion). Normal-slip separation has been retained for the pre-rift (basement) and synrift sediments below the null-point whereas the synrift sediments above the null-point and post-rift sediments show reverse-slip separation. The position of a short-cut thrust is shown. (c) Short-cut thrust in the footwall of the inverted extensional fault. (d) Expulsion of sedimentary rocks from a half-graben by slip-reversal and forward thrusting on the boundary fault and back-thrusting at the basement–cover contact. (e) Expulsion of sedimentary rocks from a half-graben by back-thrusting at the basement–cover contact and forward thrusting over the footwall by inversion of the half-graben boundary fault. (f) Rotation of the half-graben boundary fault into a thrust and thrusting at the basement–cover contact.

in the Karrat Fjord thrust system and/or because its tip-line was buried by post-rift sediments of the Nûkavsak Formation (Fig. 4a). Reactivation of extensional growth faults will cause folding of syn- and post-rift sedimentary rocks during basin inversion (Hayward & Graham 1989; Gibbs 1990). Accordingly, the Itsuakarsuk overfold is interpreted as an inversion fold formed by expulsion of the Nûkavsak Formation forwards (to the west) over the footwall of the Kangilleq Fault (Fig. 7d and e) and after thrusting in the Karrat Fjord thrust system and the emplacement of the Karrat thrust sheet.

The Inngia–Kangilleq dome complex: inversion of a NW–SE-trending extensional fault system

Inner Karrat Fjord district is dominated structurally by the Inngia–Kangilleq dome complex (Figs 3 and 4a). Overall, the axial surface trace trends NW–SE but in detail several differently oriented four-way closures are defined by structural contours drawn on the base of the Nûkavsak Formation (Fig. 3) (Henderson 1969). This complexity is assumed to reflect the architecture of the system of extensional faults that reactivated to form the dome.

Low-angle thrusts, folds and fabrics of the Karrat Fjord thrust system are folded by an upright anticline, one of the subsidiary four-way closures of the complex, just north of Niaqornakassak (Fig. 2). Here, in 2000 m high cliffs a thrust duplex system in the Karrat Fjord thrust system is exposed, comprising imbricated basement gneiss and pelitic rocks of the Qeqertarsuaq Formation (Fig. 2). The roof thrust dips gently ESE and the transport direction is defined by WNW–ESE-trending and gently ESE-plunging mineral and shape fabric lineations (Fig. 6b). Duplex thrusts cut up-section to the ESE and asymmetric porphyroblast systems confirm top-to-the-ESE transport. This is a slightly different transport direction from that of the thrusts in the Karrat Fjord thrust system farther west (Fig. 6a and b). The rocks in this stack of basement–cover horses are strongly ductilely deformed, and contain intense planar and linear fabrics and a metamorphic mineral assemblage characteristic of mid-amphibolite-facies grade (staurolite).

The cross-section in Figure 4a transects the crest of the dome on Umiammakku Nunaa (Fig. 2), where thrusts and intense fabrics in the Karrat Fjord thrust system are folded by subsidiary structures of

the dome complex. Abrupt changes in thickness and lithology in the Qeqertarsuaq Formation across discordances constrain the position of extensional growth faults (Fig. 4a). Reactivation, accompanied by back-thrusting in fault hanging walls, formed moderately to gently inclined, post-Karrat Fjord thrust system folds with east and west vergence. Metamorphic grade is lower than at Karrat. Garnet–staurolite assemblages in pelitic horizons in the Qeqertarsuaq Formation and andalusite–biotite (rarely cordierite) grew in metamorphosed siltstones and shales of the Nûkavsak Formation during or just after deformation in the Karrat Fjord thrust system before the dome complex formed.

High-quality post-world war II oblique aerial photography and geological survey maps have allowed the cross-section to be extended to the inland ice (Fig. 4a). There is no evidence of thrust duplication of basement rocks east of Johannes Bræ (Fig. 2) and the section reveals a system of reactivated extensional faults and inversion anticlines. This implies that the amount of shortening in the Karrat Fjord thrust system decreases east, concomitant with decrease in metamorphic grade. A reactivated extensional fault limits the uplifted area of the dome complex to the east and returns Kangilleq Formation to ‘regional’ in the footwall (Fig. 4a).

Implications

Partial restoration validates the geology of the deformed cross-section and reveals key aspects of basin geometry and evolution (Fig. 4a). It shows the Qeqertarsuaq Formation deposited in relatively small synrift basins in the hanging wall of normal faults. The Kangilleq Formation is post-rift with respect to these faults with a fairly uniform thickness and strong overstep unconformity across all the fault blocks (Fig. 4a). The formation is thickest in the large basin bounded by the Kangilleq Fault, which was active during deposition of both Qeqertarsuaq and Kangilleq Formations. The lower Nûkavsak Formation may be syn- or post-rift with respect to the Kangilleq Fault: the thick sequence of turbidites in the fault hanging wall does not give unambiguous evidence of growth, and is post-rift with respect to all smaller synrift basins.

Thrusting in the Karrat Fjord thrust system in the western part of the cross-section is represented by the partially restored Karrat

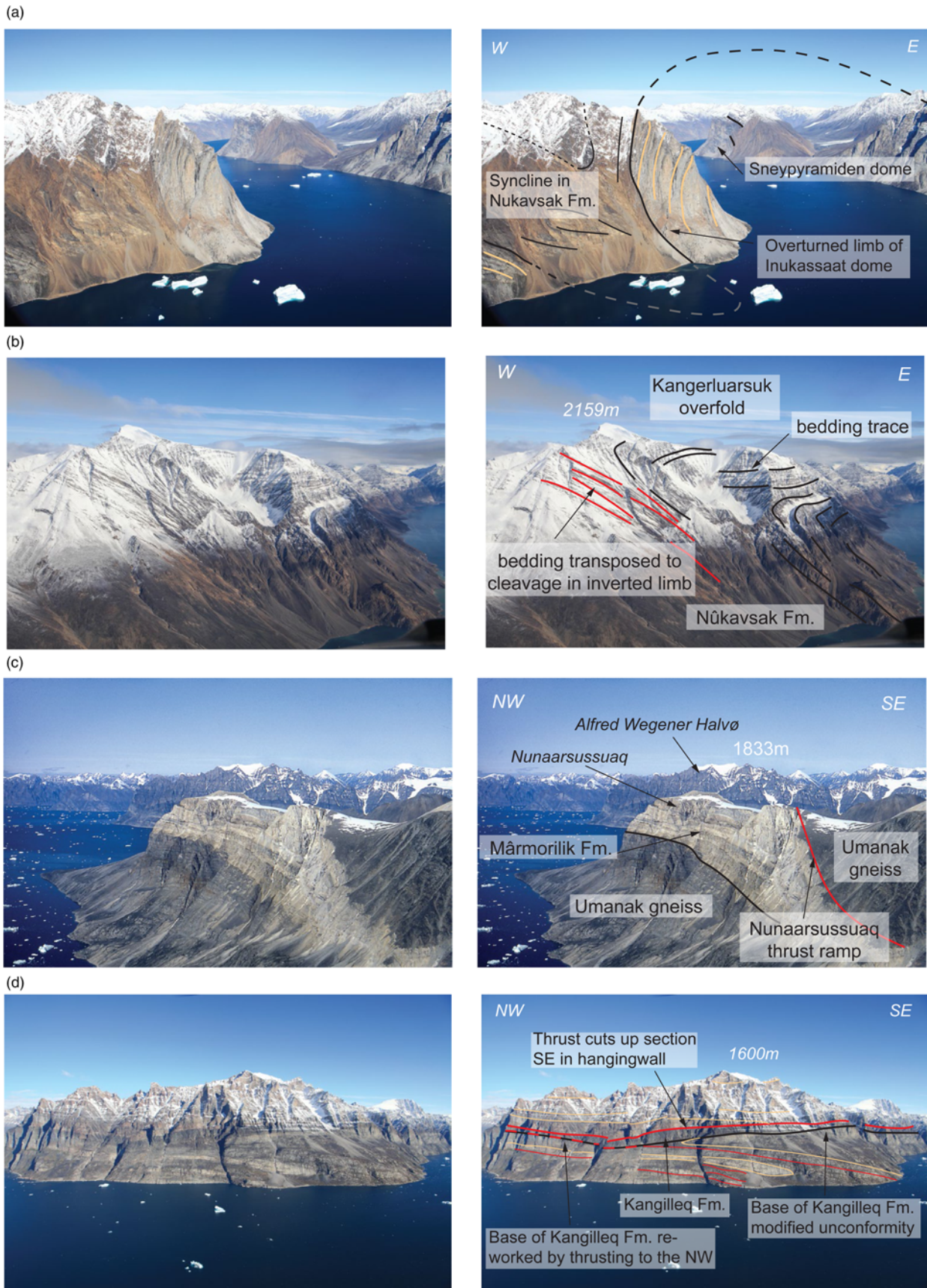


Fig. 8. Major structures of the Rinkian orogen in the Uummannaq region. **(a)** The Inukassaar dome. The anticline of the dome and complementary syncline in the adjacent Nukavsak Formation formed as fault-propagation tip-line folds above a NE-trending, inverted extensional fault. **(b)** The Kangerluarsuk overfold on the north side of Kangerluarsuk. **(c)** The Nunaarsussuaq thrust has transported a thrust sheet of Archaean basement gneiss c. 12 km to the NW above a footwall comprising carbonates of the Marmorilik Formation. **(d)** Cliffs at the western end of Alfred Wegener Halvø. The upper thrust sheet cuts up-section to the SE in the hanging wall. This thrust is thought to belong to the Karrat Fjord thrust system. The footwall is in amphibolite schist of the Kangilleq Formation. Later thrusts of the Nunaarsukassak thrust system cut up-section to the NW in the footwall with a roof thrust at the base of the Kangilleq Formation. **(e)** The Kigarsima nappe at Kigarsima, Kangerluarsuk. The nappe is defined by folding in Nukavsak Formation and in basement Umanak gneiss. The nappe is part of a fault-propagation anticline-syncline fold pair in the hanging wall of the Kigarsima thrust.

(e)

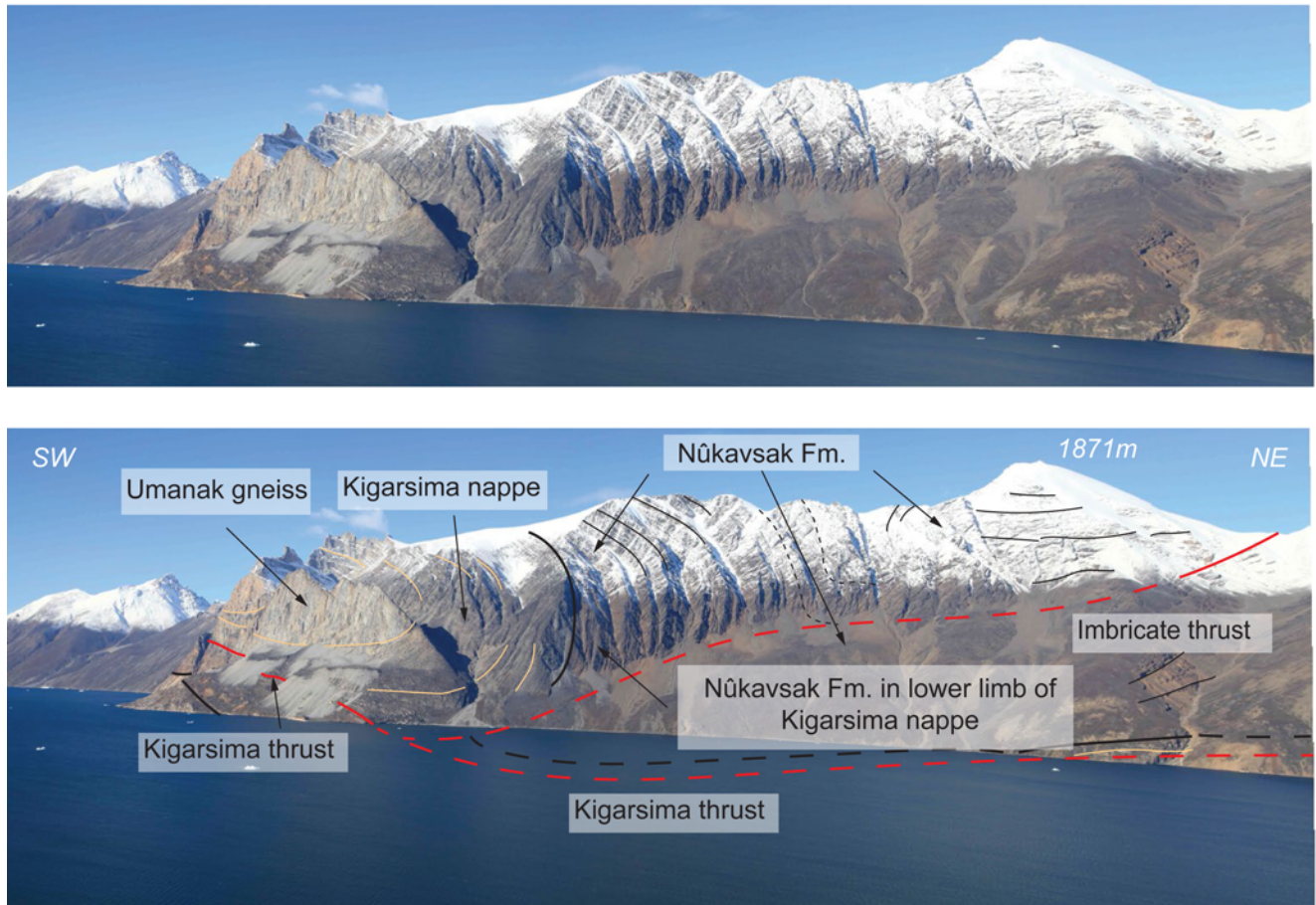


Fig. 8. Continued.

thrust. Overall, partial restoration implies that at least the upper Nûkavsak Formation oversteps half-graben architecture completely and is post-rift. It may have been deposited as a turbidite flysch in a foreland basin ahead of a thrust system, the Karrat Fjord thrust system, advancing from the west (Fig. 4a). Decrease eastward in metamorphic grade and (inferred) deformation intensity in the Karrat Group is consistent with a foreland to the Karrat Fjord thrust system located below the inland ice to the east.

The Kangilleq Fault and other major NW-trending faults (Fig. 3) are dip-slip extensional faults (headwall faults; Gibbs 1990) that bounded sub-basins in which the Qeqertarsuaq Formation was deposited. The sub-basins were subsequently inverted to form the Innigia–Kangilleq dome complex. Decrease in thickness of the Qeqertarsuaq Formation SE of the dome complex (Henderson & Pulvertaft 1987) is assumed to mark the position of another basin boundary fault. This fault strikes NE–SW at a high angle to the trend of the dome and is interpreted as a strike-slip sidewall fault (Gibbs 1990) linked with the Kangilleq Fault (Fig. 3). In conclusion, a linked system of NW-trending extensional headwall faults and SW-trending sidewall faults characterized the pre-Rinkian continental margin of the Rae craton in the Karrat Fjord district. Reactivation and inversion of this fault system generated a domain of NW-trending upright to steeply inclined domes and dome complexes superimposed on structures in the Karrat Fjord thrust system (red-coloured structures in Fig. 2).

Uummannaq Fjord district: Nunaarsussuaq thrust system and its reactivated foreland

In northern Uummannaq Fjord district, east of Upernivik (Fig. 2) the structural history is like that in Karrat Fjord district. East-directed thrusting (Karrat Fjord thrust system) predated overfolds in

the Nûkavsak Formation and dome- and basin-like folding of the basement–cover contact. The difference is that NW–SE-trending inversion folds, such as Sneppyrampen dome, traced from Karrat Fjord into Uummannaq Fjord district are refolded with a NE–SW to east–west trend (red- and yellow-coloured structures in Fig. 2) in the foreland of the Nunaarsussuaq thrust system. We describe first the structures in the reactivated foreland to this thrust system.

Inukassaat dome: an inversion anticline

The Inukassaat dome (Figs 3 and 8a) was originally interpreted to be a diapir and the dome- and basin-like pattern of the Rinkian belt was believed to be due to gravity tectonics (Henderson & Pulvertaft 1967, 1987). It was thought also that overfolds formed by gravity gliding off the rising domes (Henderson 1969) and that basement-cored nappes were a result of convective overturning of the crust (Pulvertaft 1973). The Inukassaat dome is important in testing these ideas because there are accessible exposures on the dome flanks. Exposures of Nûkavsak Formation in the steep north limb show crenulation and crenulation cleavage that verge east towards the anticlinal hinge line. The dome, and others like it, are interpreted to be buckle folds rather than diapirs driven by buoyancy. The dome and the syncline to the west (Fig. 8a) are part of a NE-trending fault reactivation system and form an interference pattern with the Sneppyrampen dome NE of Upernivik (Fig. 2).

Kangerluarsuk overfold: expulsion of sediments from a sub-basin during Rae margin inversion

Between Inukassaat and Kangerlussuaq Sermersua (Fig. 2) kilometre-scale, east-vergent chevron folds and thrusts in Nûkavsak

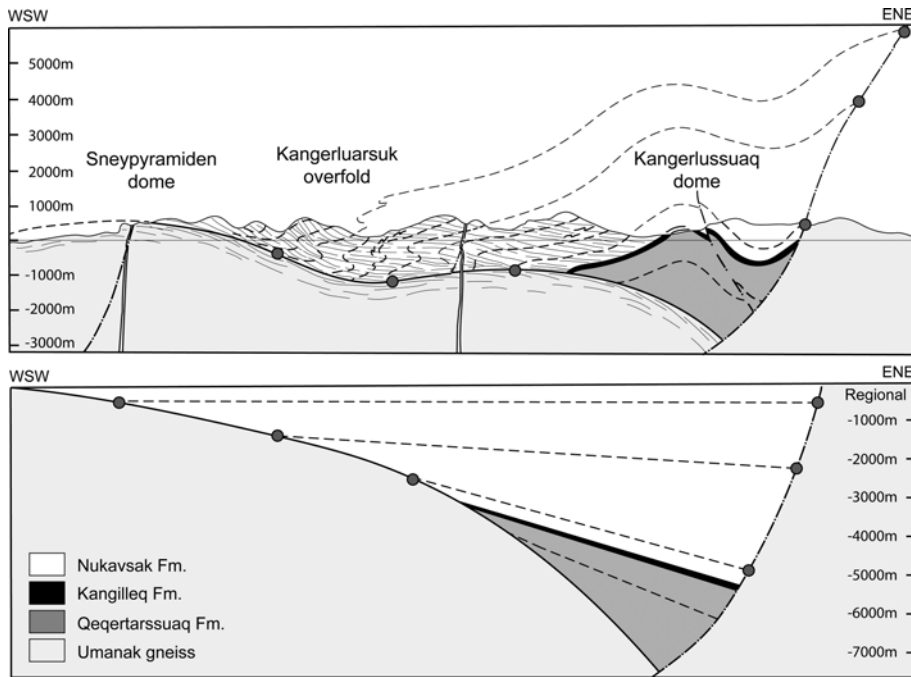


Fig. 9. Geology of inner Kangerlussuaq: the Kangerluarsuk overfold and inverted half-graben geometry.

Formation are refolded by a large-scale, west-closing recumbent fold (Fig. 9), the Kangerluarsuk overfold (Henderson 1969). The overfold can be traced south to Kangerluarsuk (Fig. 8b). The basement–cover contact shows less shortening than the Nukavsak Formation and the overfold must detach at the contact (Fig. 9). Henderson (1969) and Henderson & Pulvertaft (1987) thought that the overfold formed by gravity gliding during (diapiric) uplift of the domes. More probably, it formed above a detachment at the basement–cover contact during inversion and expulsion of Nukavsak Formation from a half-graben by displacement up a roll-over ramp at the basement–cover contact (Fig. 7d). The difference between the Itsakuarssuk and Kangerluarsuk overfolds is that in the former the Nukavsak Formation was expelled forwards over the boundary fault footwall whereas in the latter the rocks were expelled backwards up the roll-over ramp in the fault hanging wall (Fig. 7e). Farther east, the uplifted rift shoulder (Fig. 9) is a large outcrop of gneiss near the inland ice (Fig. 2). The extensional fault to the west is stitched by Melville Bugt dykes. It can be traced north to link with the reactivated fault at the east side of the Inngia–Kangilleq dome (Figs 2 and 3). The small Kangerlussuaq dome is an inversion anticline in the hanging wall of this fault (Fig. 9).

Qaarsukassak to Maarmorilik: inversion of a SW–NE-trending extensional fault system

Along the inland ice margin, domains of folding and thrust imbrication of Karrat Group sedimentary rocks and Archaean gneisses (Fig. 4b) separate domains of weak deformation in Archaean basement where the angular unconformity at the base of the Karrat Group is well preserved. At Qaarsukassak, thin-bedded fine sandstones, metasiltsstones and mudstones of the Nukavsak Formation are underlain by *c.* 80 m of Qeqertarsuaq Formation with a strong angular unconformity at the base and very weakly deformed Archaean granitic gneiss below (Figs 2 and 3). In fine-grained rocks of the Nukavsak Formation a strong, gently dipping cleavage appears to be bedding-parallel and a gently plunging biotite stretching lineation on cleavage has a NW–SE trend (Fig. 6c). Asymmetric quartz vein boudins viewed parallel to this lineation show top-to-the-SE transport and minor thrusts cut up-section to the SE (Marker & van Gool 2014). This implies that early fabrics in the Karrat Group at Qaarsukassak probably formed during

thrusting in the Karrat Fjord thrust system. However, Archaean basement was left virtually unaffected by Palaeoproterozoic deformation, except close to the unconformity.

Gently dipping bedding and cleavage were folded by large-scale dome- and basin-like folds at Qaarsukassak (Fig. 4b) and more widely in the Kangerluarsuk area. The folds are similar in style to the inversion folds of the Karrat Fjord district and the Inukassaat–Kangerlussuaq area but have an east–west or WSW–ENE trend (red- and yellow-coloured structures in Fig. 2). South of Qaarsukassak, they are part of a thrust system that imbricated cover and basement rocks and dips fairly steeply to the north (*c.* 40°) (Fig. 4b). The reverse faults strike WSW–ENE parallel to the trend of the axial surfaces of the dome- and basin-like folds, and they cut up-section to the south. This thrust system is superbly exposed on both sides of the glacier Kangerluarsuup Sermia (Figs 2 and 4b), although thrust contacts are inaccessible, which hinders determination of the transport direction and displacement sense. In siltstones and fine sandstones of the Nukavsak Formation an east–west- to WSW–ENE-trending pencil cleavage is widely developed owing to the intersection between the early (Karrat Fjord thrust system) bedding-parallel cleavage and steeply NW-dipping, thrust-related cleavage. Taken with the evidence that thrusts cut up-section to the south, this implies that transport was to the south or SSE. South of Qaarsukassak, tonalitic gneisses with I-type granite characteristics form a domain of low-strain deformation, which underlies Alfred Wegener Halvø close to the inland ice (Figs 2 and 4b).

The weakly deformed gneisses on Alfred Wegener Halvø have been uplifted on a steep fault trending WSW along Qaamarujuk (Fig. 2). This reverse fault is interpreted as a reactivated extensional headwall fault at the northern limit of the carbonate shelf on which the Maarmorilik Formation was deposited (Fig. 4b). It originally separated clastic and carbonate sub-basins of the Karrat Group. The thrust–fold structure at Maarmorilik is a shortcut system in the footwall of this fault (Figs 4b and 7c).

The Maarmorilik Formation is strongly deformed in the northern part of its main outcrop (Fig. 2). Deformation, particularly thrust repetition, decreases south. Marbles contain planar fabrics, more or less parallel to bedding, and an intense, gently ESE-plunging, mineral lineation (Garde 1978; Pedersen 1980). Asymmetric shear-sense indicators viewed parallel to the lineation indicate top-to-the-SE or -ESE transport. This is the same early fabric

development and structural history as recorded in the rocks of the Nûkavsak Formation at Qaarsukassak. The fabrics are folded by steeply north-inclined, WSW-trending folds (Pedersen 1980, 1981) related to thrusts that cut up-section to the south. Cleavage associated with folding was superimposed on earlier planar fabrics and generated an intense, gently ESE-plunging rodding/intersection lineation. Despite strong internal deformation, an angular unconformity on granitic rocks of Archaean age is preserved at the base of the formation.

Nunaarsussuaq thrust system: NW-directed thrusting

Extensional faults that cut the unconformity at the base of the Mârmorilik Formation have been reactivated and rotated by penetrative ductile deformation and thrusting SE of the main outcrop of the formation (Fig. 4b). This is the front of a major thrust system, the Nunaarsussuaq thrust system, that underlies Nunaarsussuaq and the western parts of Alfred Wegener Halvø and Qiiqi (blue-coloured structures in Figs 2 and 4c) and all of the Uummanaq Fjord district south to Nuussuaq (Fig. 2).

On Nunaarsussuaq (Fig. 2), the Nunaarsussuaq thrust cuts up-section NW and brings a thrust sheet of Archaean gneiss onto a footwall of Mârmorilik Formation (Figs 4c and 8c). A mineral lineation defined by hornblende and biotite, and a stretching lineation defined by recrystallized feldspar in augen gneiss in the thrust hanging wall, show that the extension direction plunges gently SE. The asymmetry of the feldspar porphyroclasts viewed parallel to the lineation indicates top-to-the-NW transport. There are two imbricate thrusts in the hanging wall of the Nunaarsussuaq thrust (Fig. 4c). The hanging wall of the lower thrust comprises Archaean megacryst gneiss called the Tasiussaq granodiorite (Henderson & Pulvertaft 1987). This thrust has a branch line with a higher thrust that is steeper and has tonalitic gneiss in its hanging wall (Fig. 4c). Remarkably, synsedimentary extensional faults traced west from the Maarmorilik area into Nunaarsussuaq show progressive rotation from a steep NW dip through vertical to become SE-dipping imbricate thrusts on Nunaarsussuaq in the Nunaarsussuaq thrust system (Figs 2, 4c and 7f). The Nunaarsussuaq thrust itself is not a rotated extensional fault because its footwall occupies a long thrust flat in Mârmorilik Formation. Rather, it formed as a thrust in the footwall of the lower imbricate thrust during progressive deformation in the Nunaarsussuaq thrust system (Fig. 4c).

A right-way-up section of quartzite and marble of the Mârmorilik Formation is folded into a recumbent, SE-facing syncline in the footwall of the Nunaarsussuaq thrust (Fig. 4c). Henderson & Pulvertaft (1987) thought this fold was part of a fold nappe in the hanging wall of the thrust, the Nunaarsussuaq nappe. This cannot be the case because the facing direction of the fold is SE towards the hinge zone of the proposed nappe closure. Instead we interpret the structure to be part of a SE-directed thrust system that refolded the Nunaarsussuaq thrust sheet (Fig. 4c). The structure is similar to that at Mallak (Fig. 2).

Qiiqi and Alfred Wegener Halvø: reworking of Karrat Fjord thrust system in the Nunaarsussuaq thrust system

The peninsulas of Alfred Wegener Halvø and Qiiqi are characterized by a stack of thin thrust sheets each with a cover of metavolcanic and metasedimentary rocks comprising amphibolite of the Kangilleq Formation and/or biotite schists of the Nûkavsak Formation (Fig. 4c). Ductile deformation was intense and no evidence of the angular unconformity at the basement–cover contact has been preserved. On foliation surfaces in basement and metasedimentary cover rocks, mineral lineations defined by sillimanite, biotite or hornblende and by quartz shape fabrics trend NW–SE (Fig. 6d). Asymmetric kinematic indicators viewed

parallel to the lineation show that thrust transport was top-to-the-NW. This NW-directed thrust system is probably a continuation north of the Nunaarsussuaq thrust system. At some localities in the outer part of Kangerluarsuk (Fig. 2) NW–SE-trending lineations overprint an east–west- to WSW–ENE-trending mineral lineation (Fig. 6d). The early lineation is defined by sillimanite (after kyanite), biotite and hornblende and is parallel to a lineation defined by quartz shape fabrics. Sections viewed parallel to the east–west-trending lineation show top-to-the-east kinematic indicators. The early lineation was formed in the Karrat Fjord thrust system and has been heavily overprinted in the Nunaarsussuaq thrust system between Qiiqi and Nunaarsussuaq.

Cliffs at the end of Alfred Wegener Halvø are oriented close to the thrust transport direction in the Karrat Fjord thrust system (transport to the ESE) and in the Nunaarsussuaq thrust system (transport to the NW). If the stack of thrust sheets exposed were entirely due to thrusting in the Nunaarsussuaq thrust system, then thrusts should all cut up to the NW through layering. Instead, the thrust at the top of the Kangilleq Formation cuts up to the SE in its hanging wall through a unit of strongly ductile deformed gneiss (Figs 4c and 8d). This implies thrusting to the east or ESE, consistent with top-to-the-east kinematic indicators associated with the early mineral and shape fabric lineations. Therefore, the Nunaarsussuaq thrust system has reworked an existing stack of Karrat Fjord thrust system thrust sheets formed on Alfred Wegener Halvø and Qiiqi (blue- and yellow-coloured structures in Figs 2 and 4c).

Restoration of Nunaarsussuaq thrust system thrusts returns the structure to the stage after emplacement of the upper thrust sheet on Alfred Wegener Halvø (Fig. 4c). The partial restoration shows a longitudinal section through a major Karrat Fjord thrust system thrust sheet with the extensional fault system of the rifted continental margin preserved in the footwall (foreland) below the thrust. One of the extensional faults is the boundary fault at the northern margin of the Mârmorilik Formation carbonate shelf. This was extrapolated along-strike from the Maarmorilik area into the line of the section in Figure 4c. The fault marked the boundary between clastic and carbonate basins of the Karrat Group. Like others in the footwall of the Karrat Fjord thrust system, it was segmented and rotated into a thrust orientation by intense and penetrative ductile deformation in the Nunaarsussuaq thrust system. Comparison of the deformed and partially restored cross-sections shows that the former footwall of this fault is now a thrust hanging wall in which the Mârmorilik Formation was carried NW in the Nunaarsussuaq thrust system over basement gneiss to occupy a high position in a thrust stack where it has now been eroded above Alfred Wegener Halvø (Fig. 4c).

Partial restoration shows also that the upper thrust sheet on Alfred Wegener Halvø is a regionally important structure, the Kigarsima thrust sheet, which extends north to Qiiqi (Fig. 4c). At Kigarsima, on the south side of Qiiqi (Fig. 2), a spectacular fold nappe, the Kigarsima nappe, is exposed in the hanging wall of an imbricate thrust that cuts up-section to the NW in the hanging wall of the Kigarsima thrust (Fig. 8e). Stretching lineations in ductile deformed rocks below the imbricate thrust trend NW–SE but overprint an earlier east–west-trending stretching lineation. We associate the early lineation with emplacement of the Kigarsima thrust sheet to the east and the NW–SE-trending lineation with reworking in the Nunaarsussuaq thrust system when the imbricate thrust and the Kigarsima fold nappe were formed (Fig. 8e).

Discussion

A key concept is that large-amplitude dome- and basin-like folds in the Rinkian belt are expressions of a thick-skinned style of tectonics and positive inversion of early Palaeoproterozoic basin-bounding extensional growth faults in the Rae craton continental margin. Blind headwall and sidewall faults were located and extrapolated to depth

using an iterative technique involving geological map interpretation and construction of cross-sections validated by restoration. This has highlighted two domains of pre-Rinkian extensional faults in the Rae craton margin: a northern domain in the Karrat Fjord thrust system foreland of NW-trending extensional faults linked to SW-trending strike-slip faults (Karrat Fjord district) and a southern domain in the Nunaarsussuaq thrust system and its foreland of WSW-trending extensional faults (Ummannaq district).

Apart from upright dome- and basin-like folds, other structures associated with thick-skinned inversion tectonics are large monoclines, 'overfolds', within the Nûkavsak Formation. These structures re-fold cascades of east-vergent chevron folds and formed after thrusting in the Karrat Fjord thrust system when greywacke and shale sequences were expelled from half-grabens either forward, over the boundary fault (Itsakuarssuk overfold), or backwards up the ramp formed by the roll-over anticline into the boundary fault (Kangerluarsuk overfold). They are a significant indicator of inversion tectonics.

Partial restoration of regional cross-sections shows that the Karrat Fjord thrust system propagated from west to east in a turbidite flysch megasequence (Upper Nûkavsak Formation). This sequence first filled the accommodation space remaining in rift basins after deposition of syn- and post-rift sequences (Qeqertarsuaq Formation and Lower Nûkavsak Formation). The spectra of detrital zircon ages and the composition of greywackes in the Nûkavsak Formation are consistent with derivation of the sediments from a *c.* 1.9–2.1 Ga Palaeoproterozoic source, possibly a magmatic arc (Kalsbeek *et al.* 1998; Thrane *et al.* 2003). We presume this source to have been to the west in the hinterland of the Karrat Fjord thrust system, where it may be represented by the Cumberland batholith exposed over a wide area on present-day southern Baffin Island. However, the batholith was emplaced between *c.* 1.865 and 1.845 Ga and the intrusions seem too young to be the source of the detrital zircon populations in the Nûkavsak Formation. Moreover, their petrogenesis favours formation in a post-accretion setting rather than in a magmatic arc (Thrane *et al.* 2005; Whalen *et al.* 2010). The Cumberland Batholith may well have formed in a post-accretion setting but it appears to have diverse protoliths formed during earlier continental margin processes, including abundant inherited components with the age range 1.9–2.0 Ga required to source the Palaeoproterozoic detrital zircons in the Nûkavsak Formation.

In West Greenland, the Prøven igneous complex, an I-type granite and a component of the Cumberland batholith, was emplaced at *c.* 1.87 Ga (Thrane *et al.* 2005) during ductile thrusting in the Karrat Fjord thrust system (Grocott *et al.* 1987). Because the Upper Nûkavsak Formation is younger than *c.* 1.9 Ga, this permits the conclusion that the formation was deformed soon after deposition. Based on this timing, and the geometry revealed by the partially restored cross-section (Fig. 4a), we infer that a turbidite flysch, supplied with sediment from plutonic and magmatic precursors to the post-accretion Cumberland batholith, filled the accommodation space in a foredeep ahead of a pro-foreland basin (Naylor & Sinclair 2008) that advanced west to east. Metamorphic grade in the Karrat Fjord thrust system decreases from west to east and there is a decrease in basement involvement in thrusting in this direction. We conclude that the Karrat Fjord thrust system foreland was to the east, below the present-day inland ice, and that the thrust system formed as a result of convergence and then collision between Baffin Island and West Greenland more or less along the line of present-day Baffin Bay.

The eastward thrust direction for the Karrat Fjord thrust system is at a high angle to that determined in equivalent tectonostratigraphic units in the Piling Group on Baffin Island, which has been thrust to the north (Corrigan *et al.* 2001). This is not necessarily an inconsistency, as the position and number of orogenic sutures and tectonic terrains on southern and central Baffin Island is unresolved (Wodicka *et al.* 2014, and references therein). In this respect the aim

of this paper is simply to provide some new constraints on future plate-tectonic reconstructions for the Palaeoproterozoic of the Trans-Hudson orogen in NE Canada and West Greenland.

Severe deformation has taken place in the Nunaarsussuaq thrust system, a NW-directed regional thrust system that affected most of the Ummannaq Fjord district north of Nuussuaq and that overprinted the Karrat Fjord thrust system. Although traditionally also assigned to the Rinkian orogen, the thrust front of the Nunaarsussuaq thrust system may mark the northern limit of thrusting in the Nagssugtoqidian orogen, which has an age of *c.* 1.84 Ga (Connelly *et al.* 2006). WSW-trending positive inversion structures at Qaarsukassak and Maarmorilik appear to be more or less the same age as the Nunaarsussuaq thrust system. They formed in the foreland of the Nunaarsussuaq thrust system as it propagated north and are younger than the Karrat Fjord thrust system and the inversion system in the Karrat Fjord district. MVT Pb–Zn deposits at Maarmorilik may have been emplaced during fluid migration in response to the Nunaarsussuaq thrust system advancing from the SE.

The Nunaarsussuaq thrust system propagated north in a strongly arcuate surge zone that reworked thrust sheets emplaced in the Karrat Fjord thrust system. Although the Nunaarsussuaq thrust system appears to have thin-skinned characteristics throughout much of Ummannaq Fjord, in the Maarmorilik district there are fine examples of major extensional growth faults in the Rae foreland being progressively rotated across the thrust front by intense, penetrative ductile deformation into a thrust orientation. Many thrusts in the Nunaarsussuaq thrust system are therefore likely to be reworked and reactivated passive margin extensional faults.

Conclusions

What then is the significance of our work for the idea that the Nagssugtoqidian orogen and the Rinkian fold–thrust belt are a single orogen some 1100 km wide formed by north–south convergence between the Rae and North Atlantic cratons? The regional thrust transport direction in the earliest Rinkian thrust system, the Karrat Fjord thrust system, was WSW–ENE and transport was to the ENE. Evidence from fabrics and structures shows that the Karrat Fjord thrust system existed everywhere between Nunavik and Nuussuaq, albeit heavily overprinted by ductile deformation in the Nunaarsussuaq thrust system. This implies that convergence between the Rae craton on Baffin Island and a West Greenland craton was WSW–ENE (in a present-day geographical framework) at *c.* 1.87 Ga, the age of deformation in the Karrat Fjord thrust system. We infer also that subduction polarity was to the west, below plutonic rocks of the Cumberland batholith and its pre-accretion protoliths, and that the NW-trending positive inversion system in the Karrat Fjord district formed on the lower plate continental margin at this time. In this sense the Rinkian fold–thrust belt does not represent a continuation north of the Nagssugtoqidian belt, and it was not formed by north–south convergence.

In the Maarmorilik district, the surge zone in the thrust front of the Nunaarsussuaq thrust system overprints folds, thrusts and fabrics in the Karrat Fjord thrust system. Thrusting is to the NW and this system extends at least as far south as NE Disko Bugt (Fig. 1). Intense deformation and thrusting took place farther south in the Nagssugtoqidian orogen at *c.* 1.84 Ga, significantly younger than deformation in the Karrat Fjord thrust system, and so, given its young relative age in the Ummannaq Fjord region, deformation in the Nunaarsussuaq thrust system could be of Nagssugtoqidian age albeit in the lower plate of that orogenic system (Fig. 1). However, regional NW–SE shortening in the Nunaarsussuaq thrust system is not consistent with north–south convergence in the Nagssugtoqidian orogen and neither does it fit well with the east–west trend of Nagssugtoqidian structures extrapolated across the inland ice and into East Greenland (Fig. 1).

Finally, we conclude that application of structural restoration techniques in basin analysis of Palaeoproterozoic rocks has potential to provide new insights into Proterozoic orogenic processes worldwide.

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